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APPLICATION OF DIAGNOSTIC TECHNIQUES IN IMPROVING VIBRATION AND ACOUSTIC PREDICTION

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Abstract

Numerical techniques in vibration and noise control have traditionally been implemented in a prediction-only role, primarily using the finite and boundary element methods. However, the key to this approach is to accurately represent not only the physical system but also the excitation (structural and airborne), which is challenging in most cases. Recent work has shown that diagnostic and holography techniques can be used when limited information is available regarding the system. For example, contribution analysis can be performed to assess which parts of the system are the potentially dominant noise sources. Additionally, the inverse boundary element method can be used to accurately predict both structural and aeroacoustic sources. For structural problems where excitations are not known, transfer path analysis can be performed to complement a forward finite element analysis. Several examples using a diesel engine, an engine cover, and a water-cooled chiller are presented.

1. INTRODUCTION

Numerical tools are for the most part applied to problems with an aim to predict the dynamics and acoustics of the system under consideration. Given a good model, appropriate input forces, and realistic damping, real world applications can be predicted at a fraction of the cost of prototypes. However, when numerical acoustics is considered objectively, engineers find that it is not quite the panacea they had hoped for. Today, many problems are still intractable using numerical tools in a purely predictive fashion. For example, modeling flow noise is at best an immature area at this juncture. Furthermore, forces inside machinery such as engines, compressors, or gearboxes, are difficult to measure, much less predict. Without realistic input forces and damping, numerical results must be considered critically. Additionally, if the dynamic forces are not known to any degree of certainty, the accuracy of subsequent finite element and boundary element analyses are also questionable. In these cases, analysts often resort to analyzing "what if" scenarios. While this type approach is still useful for determining the possible merits of one design over another, it is hard to escape the suspicion that many models may not resemble reality as much as one would like.

In the lack of complete information needed to accurately predict the dynamics and acoustics of a complex system, engineers must use analysis cautiously and carefully consider the modeling assumptions. Perhaps just as important, engineers should also consider alternative approaches, such as diagnostic tools, to provide information that would benefit the subsequent forward numerical predictions.

This paper discusses three diagnostic approaches: contribution analysis, the inverse boundary element method, and transfer path analysis. Contribution analysis makes use of the acoustic transfer vector (ATV) concept and measured vibration to determine which part of the system is the dominant contributor to the total sound. The inverse boundary element method (BEM) offers a non-contact method to obtain not only the surface vibration but also particle velocity as, for example, in aeroacoustic noise problems. Transfer path analysis (TPA) is a load identification technique to quantify excitations that otherwise are difficult to measure. Although diagnostic techniques require a prototype, the information obtained can provide engineers with critical information regarding the system which ultimately benefits subsequent forward predictions.

2. CONTRIBUTION ANALYSIS

Most complex sound sources can be thought of as a collection of sub-sources. For instance, the B-series Cummins diesel engine shown in Figure 1 could be broken down into several different components, each of which radiates sound and vibrates very differently from the other parts of the engine. For example, the oil pan is often a very thin, stamped steel construction, whereas the engine block is a thick casting. One would expect the nature of the vibration to differ for the two components. Understanding how these different sound radiating components contribute to the overall sound and the reason for their low or high contribution is the objective of a contribution analysis.

As an example, the engine was run at 2000 RPM with no load. The BEM mesh was painted on the engine, and vibration measurements were made at each point on the engine surface. The measured accelerations were converted to velocities, and these velocities were used as the input velocity boundary condition for all subsequent analyses. The element length for each element was approximately 2 inches, resulting in 1814 nodes.

The contribution from each part of the engine was determined by specifying the vibration boundary condition on only one part of the mesh and then assigning no vibration to the remaining mesh. In the experimental world, this is akin to covering portions of the engine with barrier material. ATVs [1,2] expedited the calculations since no further matrix solution was necessary. The indirect BEM was used to generate the ATVs, and a spherical field point mesh was created to calculate the sound power. The results for the contribution analysis are shown in Figure 2.

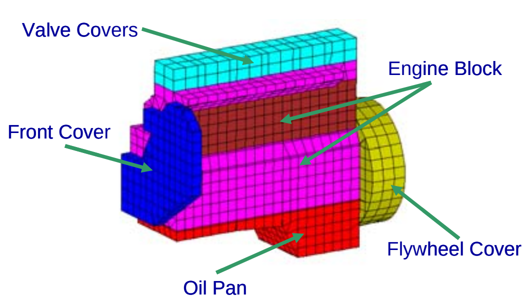


Figure 1. Schematic showing different components of the diesel engine

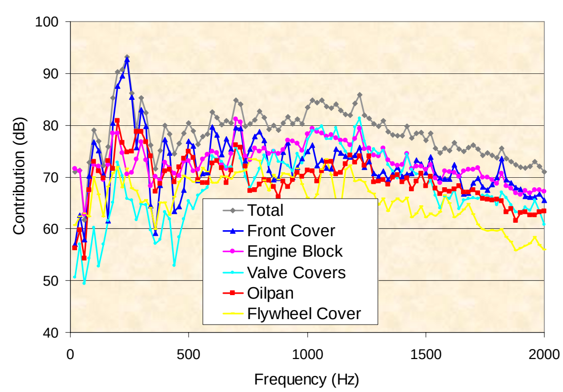


Figure 2. Contribution analysis results

The main sound contributors can be readily identified from Figure 2. Notice that the front cover is the primary contributor at low frequencies whereas the engine block and valve covers play a more vital role above 700 Hz. However, it is probably equally important to be able to identify those components that contribute little. For example, neither the oil pan nor the flywheel contributes greatly to the overall sound power. When it is taken into consideration that the oil pan is made of thin, stamped steel and has a higher vibration level than most other engine components, the aforementioned conclusion was hardly intuitive.

Further insight can be gleaned from the radiation efficiency of the different components. The radiation efficiency (σ_{rad}) is the ratio of the sound power to the power of a baffled piston having the same surface area and mean square vibration. Thus,

$$\sigma_{rad} = \frac{W_{rad}}{\rho c S \langle v_n^2 \rangle} \tag{1}$$

where W_{rad} is the radiated sound power, ρ is the fluid (air) density, c is the speed of sound, S is the surface area, and $\langle v_n^2 \rangle$ is the space-time averaged mean square vibration velocity. Usually, radiation efficiency is considered for the entire structure, but there is no reason why it cannot also be found for each component. Figure 3 shows the radiation efficiency for each component of the engine. Note the low and high radiation efficiency of the oil pan and engine block, respectively. Examining radiation efficiency answers the previously raised question of why the stiff engine block contributes more than the flexible oil pan.

Moving back to Figure 2, the highest sound power level is at 240 Hz, and the primary contributor is the front cover of the engine. A glance at the radiation efficiency in Figure 3 indicates that it is quite low for the front cover at this particular frequency. This suggests that the high sound power is not due to the front cover radiating sound so efficiently but rather because the vibration of the cover is so high. A contour plot of the operational deflection shape shown in Figure 4 reveals this to be the case. More interestingly, the engine block is the primary sound contributor at 700 Hz although an inspection of the operational deflection shape in Figure 5 below reveals that the front cover has higher vibration level. However, the radiation efficiency (Figure 3) reveals that the engine block radiates sound almost seven times more efficiently than the front cover at this frequency.

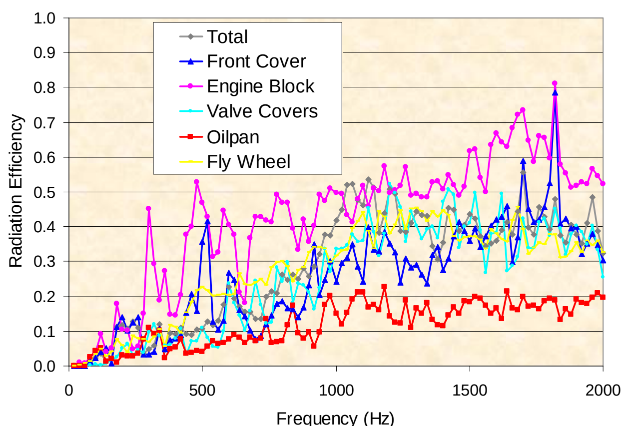


Figure 3. Radiation efficiency of the different components of the diesel engine

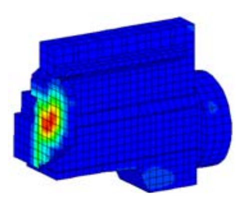


Figure 4. Operational deflection shape at 240 Hz

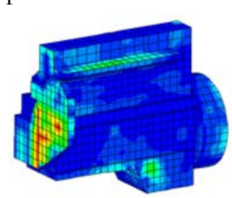


Figure 5. Operational deflection shape at 700 Hz

As discussed in the example above, the information obtained from performing a contribution analysis can be used to improve the product's design, for example by lowering the vibration level on the components that have high radiation efficiency. Additionally, the calculated radiation efficiency can be re-used with similar structures to predict the radiated sound power [3].

3. THE INVERSE BOUNDARY ELEMENT METHOD

Obtaining a detailed and accurate surface vibration of a structure is a pivotal step in an acoustic numerical prediction process. In the previous section, the surface vibration was obtained from a direct measurement at approximately 1800 points, taken over a period of several weeks. The inverse BEM [4-7] offers a faster, non-contact approach where only 6% or less points need to be measured [8]. Furthermore, in cases where the noise generation process is not completely obvious, for example in aeroacoustic applications, the inverse BEM can also be used to provide insight into the physical phenomena [9].

The inverse BEM yields the surface normal velocities using measured sound pressures at locations in the sound field. Certainly, a minimal number of measurements are desired for collecting information about the acoustic field. Accordingly, the number of measurement points is normally less than the number of BEM nodes where velocities will be computed. This results in an underdetermined problem where the solution is not unique. Moreover, in practice, the inverse BEM approach is sensitive to measurement errors unless suitable stabilizing constraints are imposed. However, an accurate reconstruction can be obtained if the required reconstruction rank is achieved while still maintaining a well-conditioned acoustic transfer matrix [10].

The inverse BEM can be used to obtain a detailed surface vibration from a limited number of measurement points. In cases where the surface is hot or moving, this non-contact approach is even more attractive. In the following example, a surface vibration reconstruction test case was performed on an engine cover. The engine cover is shown in Figure 6 along with the grid plane for microphones. The engine cover was bolted down at 15 locations to three steel plates bolted together (19 mm thick each). A shaker was attached to the engine cover by positioning the stinger through a hole drilled through the steel plates. The experiment was designed so that the engine cover could be assumed to lie on a rigid half space. The engine cover was excited with a shaker using a white noise signal inside a hemi-anechoic chamber. The sound pressure and sound power from the engine cover was measured along with the sound pressure at numerous locations above the cover. The surface vibration was reconstructed at 2148 nodes using sound pressure data measured at 15 field points located approximately 7.3 cm above the engine cover. The reconstructed surface vibration is compared with the actual vibration in Figure 7.

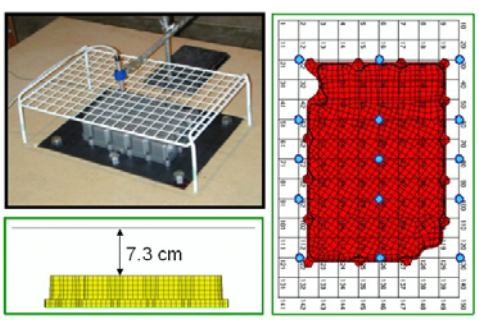


Figure 6. Setup for the engine cover test case with the field point grid

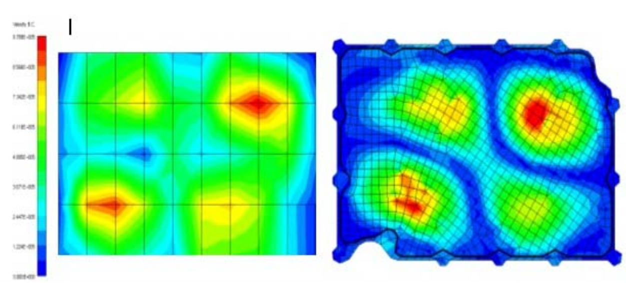


Figure 7. Surface vibration at 3000 Hz: actual (left), reconstructed using 15 field points (right)

The application of the inverse BEM for aeroacoustic applications has been discussed by the authors in a different article [11]. For this class of problems, the inverse BEM can be used to reconstruct acoustic particle velocity, which in turn can be used for forward prediction of the sound field, both in and out of the flow. Additionally, and perhaps more important, it reveals the physical phenomena of noise generation inside of the flow field which can be used as a reality check of a more traditional CFD-BEM approach in modeling aeroacoustic problems.

4. TRANSFER PATH ANALYSIS

The finite element method (FEM) has been widely utilized to predict the vibration of structures. Additionally, the surface vibration obtained from the FEM can be used in a subsequent acoustic prediction using the BEM. However, an accurate FEM prediction relies on an accurate modeling of the structure, the damping, and the dynamic loads which in most cases is challenging. Transfer path analysis (TPA) offers a diagnostic approach to obtain the necessary excitation information.

TPA is an experimental method for determining the contribution of noise and vibration sources at specified target locations [12]. With TPA, a matrix of experimental transfer functions is inverted and multiplied by operational vibration data to obtain the load functions. TPA results in an over-determined problem, in contrast to the under-determined problem faced with when using the inverse BEM.

The essential elements of a TPA procedure are illustrated in Figure 8. The first step is to identify the source and receiver (or target) locations. For example, sources can include force excitation at engine mounts or exhaust noise. Typical targets are the points of interest for sound or vibration measurements. It is important to realize that all important sources which impact a target response must be accounted for; otherwise, the TPA results will be misleading.

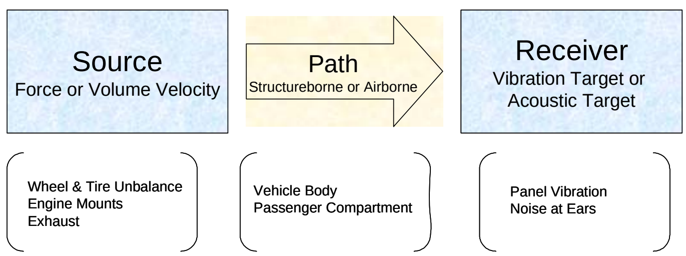


Figure 8. Elements of TPA

The next step is to identify additional measurement points (called indicator points). Indicator points are locations where additional vibrations and/or sound pressures are measured to improve the reliability of the TPA process. The number of targets plus indicator positions should be at least three times the number of source locations [12]. Transfer functions are then measured between each source and each target or indicator location. These transfer functions are measured with the sources in the off condition (or removed from the structure). The next step is to measure the response at the indicator positions during normal operation. The final step is to calculate the input forces or sound sources by inverting the transfer function matrix and multiplying it by the measured indicator responses. The contribution of each input to the vibration or sound at a target point can be determined by multiplying the input by the appropriate transfer function [12].

Trane's water cooled chiller with a rotary compressor is considered as an example to demonstrate TPA. Specifically, dynamic forces generated by the source (compressor) are estimated using TPA. Figure 9 illustrates a source-path-receiver model of a water cooled chiller with a rotary compressor. Here the source is a rotary screw compressor that transfers excitation to two attached metal pipes via a structural path and by a fluid path of pulsating refrigerant. In addition, there is some degree of interaction between structural excitation and fluid excitation within pipes and other structures downstream of the source. Moreover, the structural and fluid excitation levels change with changes in operating conditions. These inherent source complexities complicate the prediction and/or measurement of source excitations, which are used as inputs to numerical models; this can result in unrealistic prediction of operational surface velocities and radiated sound of the compressor and attached components.

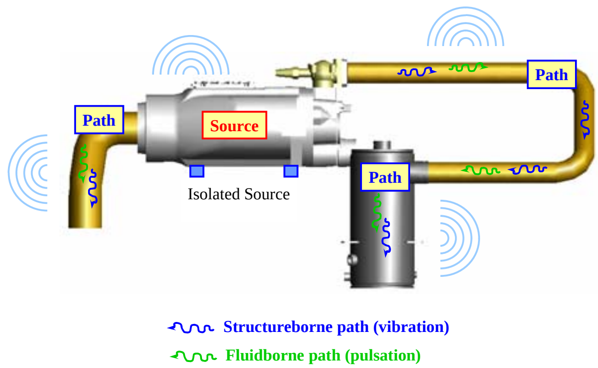
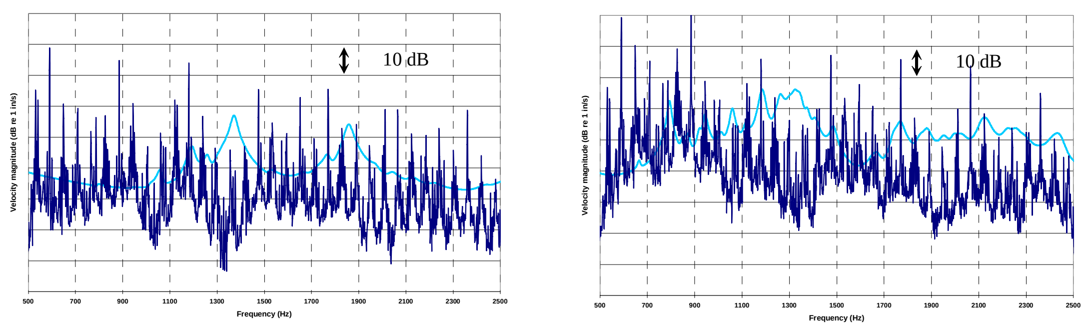


Figure 9. Source-path-receiver model for a typical water cooled chiller with a rotary compressor

Traditionally, FEM models are used to predict operational vibration of the compressor, attached components, and the entire chiller structure, often without knowledge of the dynamic load characteristics. Specifically, one or more uncorrelated dynamic forces with unity magnitude is applied near physical excitation locations or source locations. The dynamic response on the compressor and attached pipes are calculated at several points considered as target points. Figure 10 shows a comparison between predicted and measured vibration on the compressor and on one of the attached pipes.



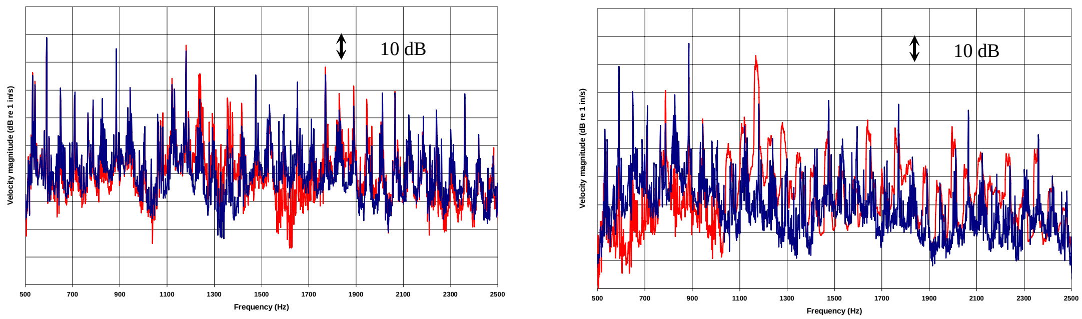
(a) Compressor (b) Discharge Pipe

Figure 10. Predicted (traditional) vs. measured rms operational vibration.

predicted (traditional), and measured

The traditional approach is inaccurate in predicting operational vibration (surface velocity) and, hence, radiated sound power of components and systems when used in a BEM analysis. The advantage of this approach, however, is in the evaluation of various design concepts and 'what if' scenarios. However, the ability to accurately predict operational vibration can help evaluate the dynamics of the structure and fine-tune the product design.

As a first attempt to estimate the dynamic forces on the source (compressor), five source points on the compressor and ten target points or thirty response degrees of freedom (DOFs), on the compressor only, were considered. Using TPA, complex dynamic forces at five target points were calculated using the LMS Virtual Lab TPA module. The calculated complex forces were then used as inputs in a forward prediction using the FEM. Harmonic forced response analysis up to 4000 Hz was performed and the dynamic response magnitude of the compressor and the attached pipe was predicted as shown in Figure 11. Predicted and measured operational vibration of the compressor shows close agreement. However, agreement is not as good on the pipe but shows significant improvement compared to the traditional approach of uncorrelated unity excitations.



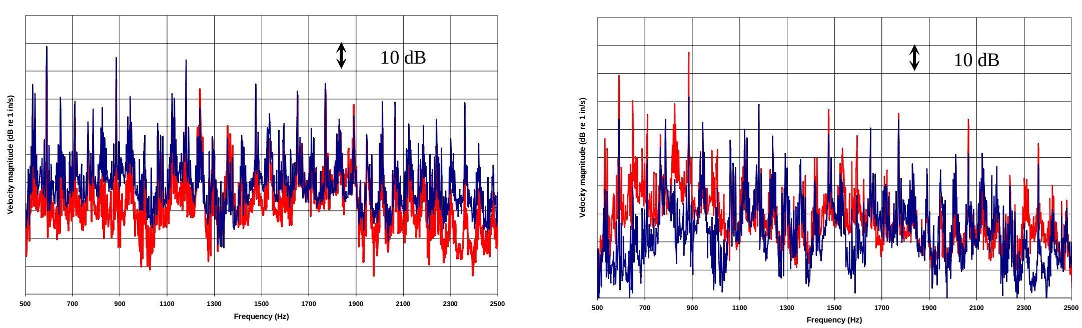
(a) Compressor (b) Discharge pipe

Figure 11. Predicted (TPA) vs. measured rms operational vibration

predicted (TPA), and measured

A comparison of Figures 10 and 11 clearly indicates that the FEM forward prediction using TPA-based excitation forces shows significant improvement over the traditional approach of uncorrelated unity excitations. The dynamic force spectrum at identified source points can be used in other structures having the same or similar source. This capability increases the accuracy of concept design evaluations and 'what if' scenarios.

In the first TPA attempt, neither target points (DOFs) on the pipe nor transfer functions between source and pipe were selected for dynamic force calculation. As a second attempt to improve the prediction of the attached pipe, an additional five target points or 15 DOFs on the attached pipe were included. A new set of complex dynamic forces at five source points were calculated. The surface velocity magnitude was predicted using the new forces in the original FEM model. Figure 12 shows a comparison between predicted and measured overall vibration.



(a) Compressor (b) Pipe

Figure 12. Predicted (TPA-2) vs. Measured rms operational vibration.

predicted (TPA-2), and measured

Figure 12(a) shows that the new set of forces calculated with additional target points on the pipe decreases the accuracy of source vibration prediction. At the same time, the prediction of operational vibration on the attached pipe is improved compared to the one obtained using the first set of TPA forces (see Figure 12(b)), although still not an acceptable accuracy when compared with measurement. Therefore, the selected five source points which predict the compressor vibration accurately are not sufficient to model the vibration level on the pipes, most likely due to the absence of an additional discharge pulsation source model. Although the results presented above can certainly be improved, they are encouraging and demonstrate the promising capability of TPA.

5. CONCLUSIONS

Three acoustic diagnostic techniques have been discussed in this paper. The primary goal of these techniques is to assist numerical acoustic predictions when there is limited information regarding the system. Contribution analysis can be used to evaluate the dominant components of a product to sound radiation and, therefore, is an excellent tool in evaluating design changes. When the source information is not available, the inverse BEM can be used to speed up the measurement process or to obtain the surface vibration or particle velocity when direct measurement is not possible. The general nature of the inverse BEM has made it an excellent technique in handling complex problems, for example the engine cover discussed herein. In cases where not only acoustic but also structural dynamic prediction is desired, the TPA approach can be utilized to provide the location, magnitude, and relationship between the complex excitations that exist in the system.

Although the techniques presented in this paper require measurements to be performed on a prototype, they provide engineers with critical information necessary to evaluate products and to optimize their design rapidly with a high level of confidence. No matter how attractive a purely numerical simulation approach is, its accuracy is severely limited by the ability to model in detail each and every aspect of the physical system, which in most cases is challenging if not impossible.

REFERENCES

[1] M. Tournour, I. Cremers, and P. Guisset, "Inverse Numerical Acoustics Based on Acoustic Transfer Vectors", *Proc. 7th International Congress on Sound and Vibration*, Garmisch – Partenkirchen, Germany, 2069-1076 (2000).

[2] F. J. Fahy, "The Vibro-Acoustic Reciprocity Principle and Applications to Noise Control", *Acustica*, **81**, 544-558 (1995).

[3] F. Martinus, B. Rockwood, and B. Boecker, "The Use of Numerically Calculated Radiation Efficiency to Improve Sound Power Prediction based on Measured Vibration", *LMS User's Conference*, Troy, MI, March 20-21, 2007.

[4] W. A. Veronesi and J. D. Maynard., "Digital Holographic Reconstruction of Sources with Arbitrarily Shaped Surfaces", *J. Acoust. Soc. Amer.*, **85**, 588-598 (1989).

[5] B. K. Kim and J. G. Ih, "On the Reconstruction of the Vibro-Acoustics Field Over the Surface Enclosing an Interior Space using the Boundary Element Method", *J. Acoust. Soc. Amer.*, **100**, 3003-3015 (1996).

[6] A. F. Seybert and F. Martinus, "Forward and Inverse Numerical Acoustics for NVH Applications", *Proc. 9th International Congress on Sound and Vibration*, Orlando, FL, 714-721 (2002).

[7] A. Schuhmacher, et al., "Sound Source Reconstruction Using Inverse Boundary Element Calculations", *J. Acoust. Soc. Amer.*, **113(1)**, 114-127 (2003).

[8] A. F. Seybert, F. Martinus, and D. W. Herrin, "Three Experiments using the Inverse BEM for Source Identification", *The International Congress NOVEM 2005*, Saint Raphael, France, April 18-21 (2005).

[9] F. Martinus, D. W. Herrin, Z. Tao, and A. F. Seybert, "Identification of Aeroacoustic Noise Sources using Inverse Boundary Element Method", *SAE Noise and Vibration Conference*, Traverse City, MI, May 16-19 (2005).

[10] F. Martinus, D. W. Herrin, and A. F. Seybert, "Practical Considerations in Reconstructing the Surface Vibration using Inverse Numerical Acoustics", *SAE Noise and Vibration Conference*, Traverse City, MI, May 5-8 (2003).

[11] F. Martinus, D. W. Herrin, and A. F. Seybert, "An Advanced Noise Source Identification Technique using the Inverse Boundary Element Method", *Proc. 2005 National Conference on Noise Control Engineering (NOISE-CON)*, Minneapolis, MN, October 17-19 (2005).

[12] A. Vecchio, et al., "Experimental Transfer Path Analysis of a Hybrid Bus", *SAE Noise and Vibration Conference*, Traverse City, MI, May 16-19 (2005).